Effect of Grating Detuning on Holographic Data Storage

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ABSTRACT

We use the scalar diffraction theory to analyze the grating detuning effect in a volume holographic data storage system. The general formulas for describing the two-dimensional distribution of retrieved image under the detuning effect have been derived. In terms of the image uniformity and the pixel shift of the retrieval image, computer simulations are used to perform a quantitative analysis.

Keywords: Holographic data storage, Grating detuning, Shrinkage effect, Scalar diffraction theory.

1. INTRODUCTION

Holographic dada storage has been considered as one of the next generation information storage technologies because of its distinct advantages of large storage capacity and fast data access rate [1]. One of unique benefits of the holographic data storage is the parallel nature of the readout; a given reference beam can retrieve large number of data pixels simultaneously to be imaged onto a 2-D detector array. The optical alignment of such a system for matching the corresponding pixels between the input Spatial Light Modulator (SLM) and the output detector array is therefore very important such that the recorded data can be retrieved correctly. To achieve this goal, a good optical imaging system with small aberration is required to achieve high precise optical alignment between the input and the output devices [2]. However, the retrieved data may not be identical to the original one, if distortions of the holographic material occur during (or after) the holographic recording. The main reasons for this data error, other than the optical misalignment, are that some recording materials possess properties of the bulk-index and/or the dimensional changes such that the recorded refractive index grating has different grating spacing from that of the light interference fringes. As a result, the Bragg condition for volume holograms is lost and the recorded information cannot be readout completely. This is called as grating detuning effect. These effects can be induced by either the chemical reactions of the materials during the recording (which is called the shrinkage (or expansion) effect [3]) and/or the environmental changes (such as the thermal expansion induced by the temperature change)[4]. In this paper, we present a theoretical analysis of the grating detuning effect induced by the dimensional changes in volume holographic material. Scalar diffraction theory (also known as "Born approximation") has been utilized to describe the two-dimensional optical distribution on the output plane. We then evaluate pixel mis-registrations and non-uniformity diffraction efficiency of the retrieval data page. The results show that the both pixel mis-registrations and non-uniformity of the retrieval data page can be reduced as the recording angle is reduced.

2. THE PRINCIPLE OF GRATING DETUNING

Referring to Fig. 1, we consider a holographic data storage system in which the center of the holographic recording medium sits at the Fourier plane of the object image. Assume that N=2M+1 holograms are stored in one location of the recording material by using the angle multiplexing technique. Those holograms are labeled as m=-M, -M+1...,-1,0,1,....M-1, M. During the recording process, the images were sequentially displayed at the object plane (x_0, y_0), illuminated by a plane wave, and were Fourier-transformed onto the rear focal plane of lens L_1, which is represented by (x, y). At the same time, a series of reference plane waves $R = \exp(-i\mathbf{k}_m \cdot \mathbf{r})$ were incident at 2M+1different incident angles for each recording, where

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θ represents the incident angle of the reference beam to record the *0*th hologram. The interference patterns formed by the object beams and the reference beams were recorded in the holographic medium as a perturbation of the refractive index. During the readout process, each of the recorded image was reconstructed from the hologram by the corresponding reference beam and then was inverse Fourier-transformed onto the rear focal plane of lens L_2, which is represented by (x_1, y_1). In an ideal case, the retrieved image should be exactly identical to the original input image. In reality, a small Bragg-mismatch resulting from grating detuning would lead to a distortion of the retrieved image.

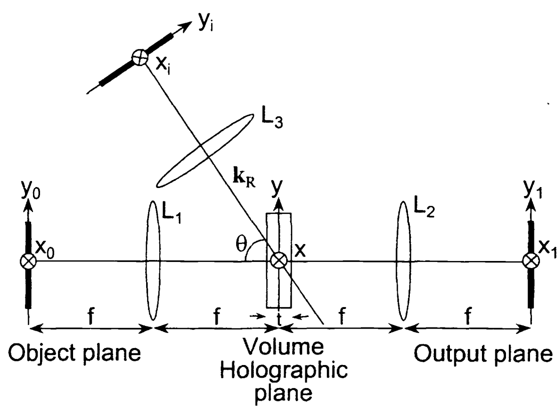

Figure 1. A Fourier holographic memory system where the recording medium is located at common Fouier plane of lenses L_1 and L_2.

The optical field of the reconstructed image can be described by scalar diffraction theory known as "Born approximation", which was established by Gu *el* etc [5] for the case without grating detuning effect. Following the similar procedures, and assuming the transverse dimension of the recording medium is much larger than the spatial bandwidth of the object image, then the reconstructed image with the grating detuning effect is given by

$$g(x_1, y_1) \propto \sum_{m=-M}^{M} f_m\left(-\frac{1}{(1+\alpha_x)}\left(x_1 + \frac{\lambda f}{2\pi}\Delta K_{mix}\right), -\frac{1}{(1+\alpha_y)}\left(y_1 + \frac{\lambda f}{2\pi}\Delta K_{miy}\right)\right)$$
$$\times\, t\,\mathrm{sinc}\left[\frac{t}{2\pi}\left(\Delta K_{miz} + \frac{2\pi}{\lambda f^2}\left[x_1^2 + y_1^2 - \left[\frac{(1+\alpha_z)}{(1+\alpha_x)^2}\left(x_1 + \frac{\lambda f}{2\pi}\Delta K_{mix}\right)^2 + \frac{(1+\alpha_z)}{(1+\alpha_y)^2}\left(y_1 + \frac{\lambda f}{2\pi}\Delta K_{miy}\right)^2\right] + \alpha_z f^2\right]\right)\right] \quad (1)$$

and the pixel displacements in lateral directions for the m*th* reconstructed image on the (x_1, y_1) plane can be derived as

$$\Delta x_1 = -\alpha_x x_0 - \frac{\lambda f}{2\pi}\Delta K_{mix},$$
$$\Delta y_1 = -\alpha_y y_0 - \frac{\lambda f}{2\pi}\Delta K_{miy} \quad (2)$$

where $\mathbf{\Delta K}_{mi}=\mathbf{k}_m'-\mathbf{k}_i = \lfloor k_{mx}(1+\alpha_x) - k_{ix}, k_{my}(1+\alpha_y) - k_{iy}, k_{mz}(1+\alpha_z) - k_{iz} \rfloor$, $\mathbf{k}_m'$ is the wave vector of the *m*th reference beam after grating detuning, and $\mathbf{k}_i$ is the wave vector of the input reading beam, the subscripts x, y, z indicate the corresponding components at x-, y- and z-directions, t is dimension of the recording medium in z-direction, α_x, α_y and α_z are the dimensional shrinkage ratio along the three directions, respectively, $f_m(x_0, y_0)$ is the *m*th input image, $g(x_1, y_1)$ is the retrieved image, and *f* is focal length of the lens.

Equation (1) contains a signal term and noise terms. Assume that the reading beam is identical to the original reference beams during reading, then the term $\mathbf{k}_m = \mathbf{k}_i$ can be considered as the signal term, which is the *m*th reconstructed image.

Other terms in relation (1) with $\mathbf{k}_m \neq \mathbf{k}_i$ give rise to the cross-talk noise. When there is no grating detuning, $\Delta\mathbf{K}_{mi}=0$, and then the signal term is exactly identical to the original input image. The noise terms consist of all other images with $m \neq i$, which are shifted patterns with reduced amplitudes modulated by sinc functions. The amounts of shift and amplitude reduction depend on the momentum mismatch $\Delta\mathbf{K}_{mi}$ between the reading beam and the corresponding reference beam. However, under grating detuning case, the momentum mismatch $\Delta\mathbf{K}_{mi}$ is not zero even when the reading beam is identical to one of the reference beams. As a result, both the image shift and amplitude reduction occur in the cross-talk noise terms as well as in the signal term. Therefore, if the photodetector array was still placed at the imaging position before recording, then the image distortion would result in mis-registrations and non-uniformity diffraction efficiency of each pixel on output device. The accuracy of the retrieved data will then be greatly reduced. In the following, we concentrate on discussing detuning effect on the signal term.

We consider the detuning effect induced by the dimensional shrinkage in the photopolymer medium. Assume that the reading beam is directed at the condition as that of the original reference beams, in which wave vectors of all beams are in the incident plane (y-z plane). From Figure 1, the components of the wave vector of the reference and reading plan waves are determined by the positions of the point sources at the reference plane, which is in the front focal plane of the lens L3. The momentum mismatch $\Delta\mathbf{K}_{mi}$ can therefore be written as

$$\begin{aligned}
\Delta K_{mix} &= 0, \\
\Delta K_{miy} &= \frac{2\pi}{\lambda}\left[-\cos\theta\frac{y_m(1+\alpha_y)-y_i}{f}+\sin\theta\frac{y_m^2(1+\alpha_y)-y_i^2}{2f^2}-\alpha_y\sin\theta\right], \\
\Delta K_{miz} &= \frac{2\pi}{\lambda}\left[\sin\theta\frac{y_m(1+\alpha_z)-y_i}{f}-\cos\theta\frac{y_m^2(1+\alpha_z)-y_i^2}{2f^2}+\alpha_z\cos\theta\right]
\end{aligned} \tag{3}$$

Notice that the above equation has been achieved under the paraxial approximation. Substituting equation (3) into equation (1), the signal term can be given as

$$\begin{aligned}
g(x_1,y_1) \propto\ & f_m\left(-\frac{1}{(1+\alpha_x)}x_1,\ -\frac{1}{(1+\alpha_y)}\left(y_1-\alpha_y\left(y_m\cos\theta-\sin\theta\frac{y_m^2}{2f}+f\sin\theta\right)\right)\right) \\
& \times t\,\mathrm{sinc}\left[\frac{t}{\lambda}\left(\alpha_z\left(1+y_m\sin\theta-\cos\theta\frac{y_m^2}{2f}+\cos\theta\right)\right)\right. \\
& \left.+\frac{1}{f^2}\left[x_1^2\left(1-\frac{(1+\alpha_z)}{(1+\alpha_x)^2}\right)+y_1^2-\left(\frac{(1+\alpha_z)}{(1+\alpha_y)^2}\left(y_1-\alpha_y\left(y_m\cos\theta-\sin\theta\frac{y_m^2}{2f}+f\sin\theta\right)\right)^2\right)\right]\right]
\end{aligned} \tag{4}$$

And also from Eq. (2), we can obtain the amount of shift of the retrieved image. Because of $\Delta K_{mix}=0$, there was only magnification but no pixel-shifts in the x_1-direction, and there are both shift and magnification of the image in y_1-direction. Those magnification and shift effects will induce pixel mis-registrations such that the accuracy of the retrieved data degrades. It can also be seen that the shift and magnification distortion of the retrieved image only depends on the shrinkage coefficients of the transverse directions. However, the diffraction efficiency of the retrieved image is modulated by a sinc-function profile, which is a function of the writing angle, the shrinkage coefficients along y- and z-directions, and thickness of the material. This provides us a guideline to analyze the signal-to-noise ratio of the signal distribution on output plane.

3. COMPUTER SIMULATION

As described in section 2, the shift and magnification as well as the distribution of the diffraction efficiency of the retrieved signal term are the functions of the material parameters and the recording configuration. To provide a better understanding of the effect of grating detuning, we evaluate the output field of each retrieved image by using typical values. We assume the size of the input image=1x1cm^2, $\alpha_x=\alpha_y=\alpha_z=0.005$, t=50μm, f=10cm, pixel size=100x100μm, and λ=514nm. For simplification, we take a example for the central (*0*th) image, in which the reading beam is directed at the original reference beam of $y_m=y_i=0$. Figure 2 shows the original and retrieved images with the angle of $\theta=15^0$. It is seen that the retrieved image has non-uniform distribution along the both x_1 and y_1 directions, although the pixel-shifts can not be seen clearly. By inserting the recording condition into Eq. (2), it can be estimated that the shift of the retrieved image about two pixels. The non-uniformity problem is more serious because the envelope of the retrieval image is modulated by a 2-D sinc function, as indicated by the second term in Eq. (4). The distribution of the retrieved image along y_1 axis is plotted in Figure 3 for various angles with $\theta=5^0$, 15^0, 30^0. It is seen that the distribution is more uniform if we use smaller writing angle, though smaller recording angles give lower diffraction efficiency.

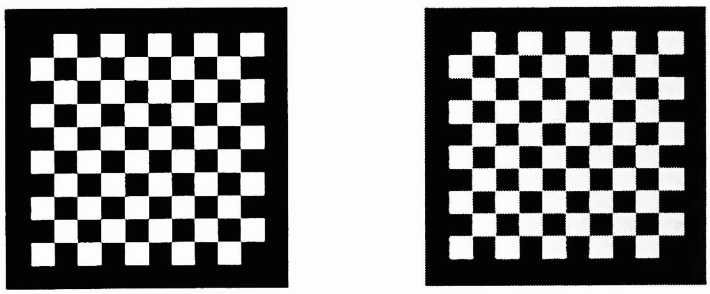

Figure 2. (a) the original input image; (b) the retrieved image under grating detuning effect.

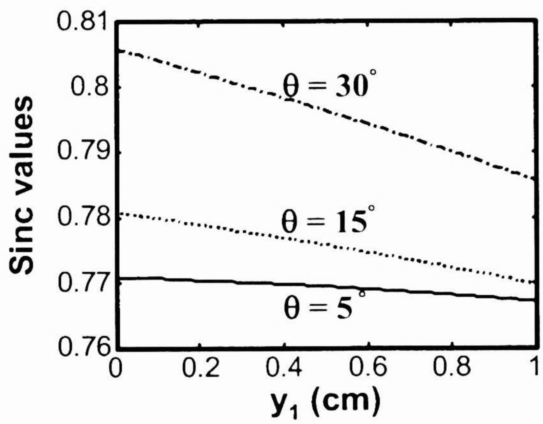

Fig. 3 The distribution of the retrieved image along y_1 axis for various writing angles.

Figure 4 shows the pixel shift as a function of the location of the output plane (x_1, y_1) for the case of $\theta=30^0$. As we predicted, the shift along the x_1-axis is independent with the writing angle and location along x_1-axis, because only magnification occurs at the x_1-axis. On the other hand, pixel-shift along the y_1-axis contains both magnification and shift effects. Considering all these distortions together, it is impossible to make a compensation of the grating detuning effect simply by moving output device.

4. CONCLUSION

In summary, by using the Born approximation for the scalar diffraction theory, we have investigated the grating detuning effect in a volume holographic storage system. The formulas for evaluating the two-dimensional distribution of the retrieved image on the output plane have been derived. They provide us a guideline to characterize the performance of a holographic storage system in terms of the image uniformity and the pixel shift of the retrieved image. Computer simulations show that the smaller writing angle provides better uniformity in diffraction efficiency. However, the diffraction efficiency of using smaller writing angles is smaller than that when using the larger writing angles.

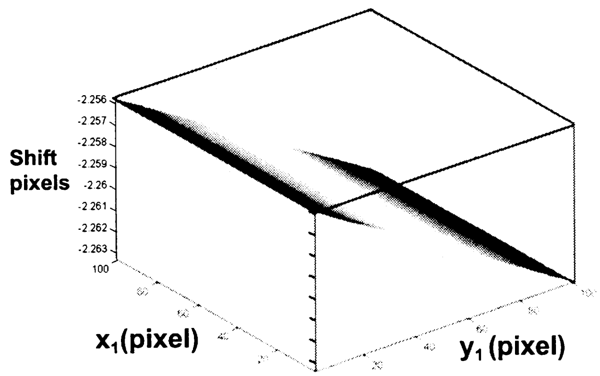

Fig. 4. The pixel shift as a function of the location of the output plane (x_1, y_1) for the case of $\theta=30^0$

5. ACKNOWLEDGEMENT

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